Development of a New Generation of High-Temperature Thermoelectric Unicouples for Space Applications

Direct Thermal-to-Electrical Energy Conversion
San Diego, CA
August 2006

presented by

T. Caillat

co-authors

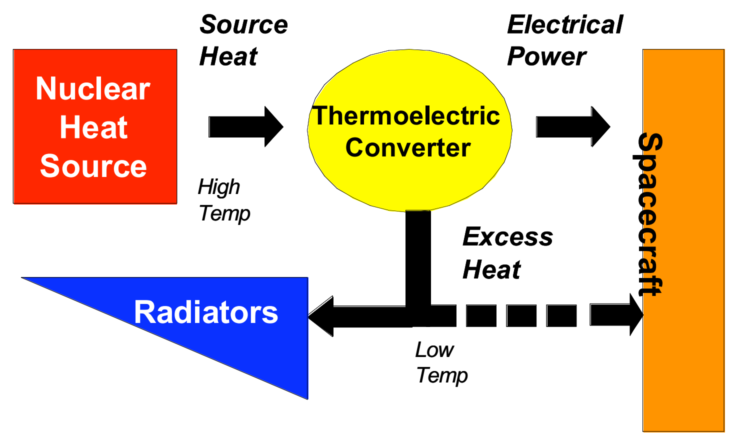
P. Gogna, J. Sakamoto, A. Jewell, J. Cheng, R. Blair, J. -P. Fleurial, and R. Ewell

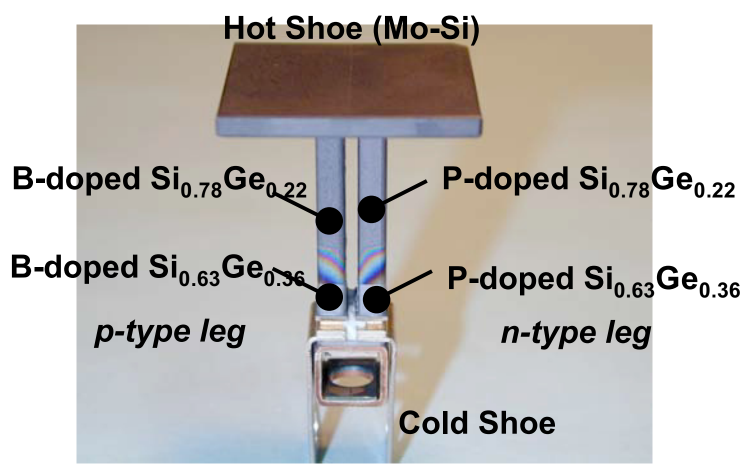
Jet Propulsion Laboratory/California Institute of Technology

What is a Radioisotope Thermoelectric Generator?

- Long life, high reliability DC electrical power source
- Converts heat from a radioisotope heat source to electricity
- Contains a nuclear radioisotope heat source, thermoelectric converter and a radiator
- Thermoelectric converter contains many couples connected in series and parallel networks
- Unicouples consist of two semiconductor thermoelectric legs (p and n) placed between hot and cold temperatures
- Efficiency of the couple depends on the thermoelectric properties of the unicouple (ZT) and temperature difference between hot and cold ends

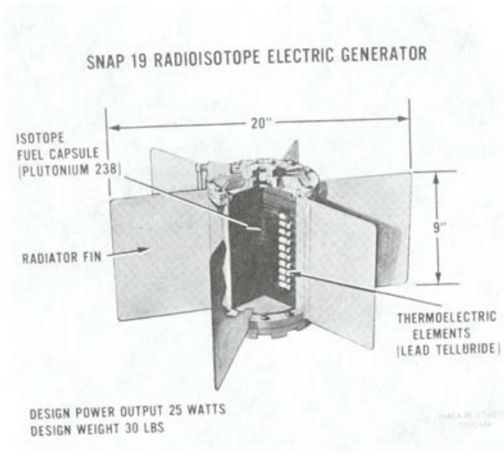
$$\eta = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \qquad Z = \frac{\alpha^2}{\rho\lambda}$$





GPHS SiGe unicouple

Flight Demonstrated Radioisotope Thermoelectric Generators
(3 Most Recently Flown Designs)



SNAP-19(PbTe RTG)
(1960-70's)

40.3 Watts (BOM)
6.2 % sytem efficiency
3 We/kg

22.86 cm (9.0 in) long
50.8 cm (20 in) dia
~13 kg (28.6 lb)
PbTe Thermoelectrics

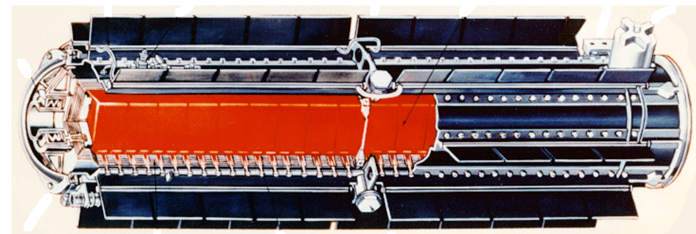
Nimbus B-1/III, Pioneer 10/11, Viking 1/2

SiGe MHW RTG
(1970's)

158 We (BOM)
6.6 % system efficiency
4.2 We/kg

58.4 cm (23 in) long
39.7 cm (15.64 in) dia
38 kg (83.7lb)
SiGe Thermoelectrics

LES 8/9, Voyager 1/2



SiGe GPHS RTG
(1980-2006)

285 We (BOM)
6.8% system efficiency
5.1 We/kg

114 cm (44.9 in) long
42.7cm (16.8in) dia
56 kg (123 lb)
SiGe Thermoelectrics

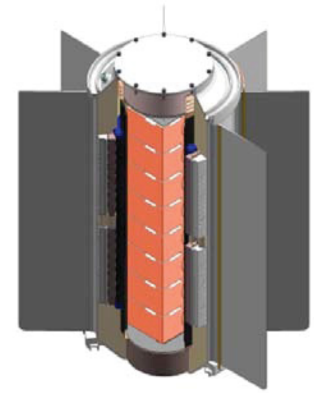
Galileo, Ulysses, Cassini & New Horizons

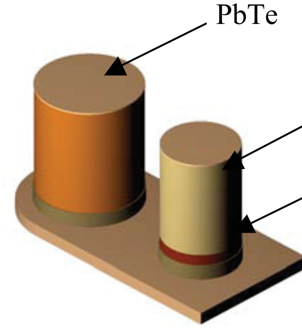
MMRTG Characteristics

- Electrical Power Output: ~ 123 W (BOL)
- Specific power: ~ 2.8 W_e/kg
- System Efficiency ~ 6.2%
- Voltage 28 VDC
- In-space & surface operational capability
- Qualified for 0.2 g^2/Hz random vibrations
- Mission life design ~14 years

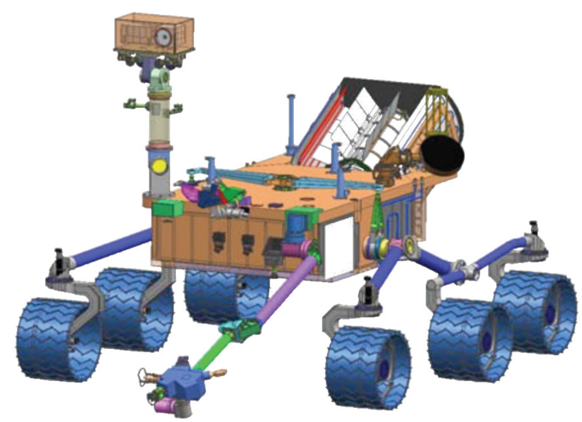
- Mass: ~ 44.1 kg
- Dimensions (half that of GPHS-RTG):
  - Length ~64 cm
  - Diameter ~64 cm
- 8 GPHS modules
- Thermal Power Input ~ 2000 W (BOL)
- 768 PbSnTe/TAGS+ PbTe couples
  - T_{hot} ~ 811 K;
  - T_{cold} ~ 483 K

MMRTG





PbSnTe/TAGS+ PbTe couples



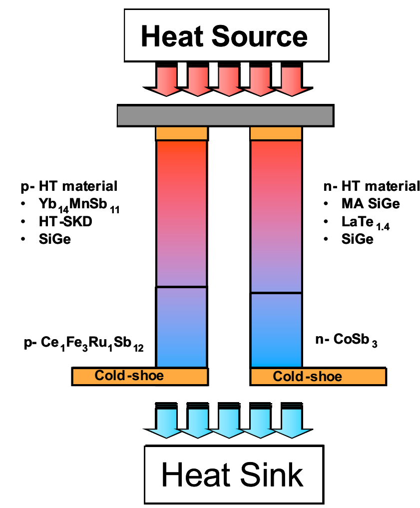
Mars Science Laboratory (MSL)

MMRTG Under Development For MSL And Other Future Deep Space And Surface Missions

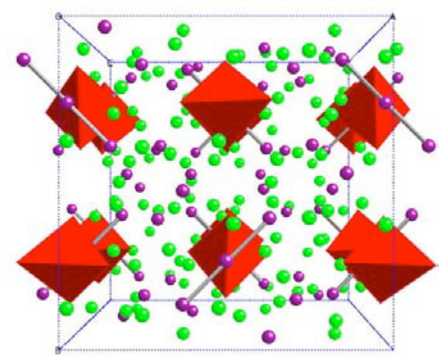
NASA Advanced RTG Needs

	Near Term (~2015)	Long Term (>2020)
Specific Power (W/kg)	6 - 8	> 10
Readiness	2015 - 2016	> 2020
Lifetime	> 14 years < 22% degradation	> 14 years < 22% degradation
Heat Source	Step 2 GPHS (8 to 12 units)	Step 2 GPHS (1 to 12 units)
System Efficiency (%)	10	13 - 15

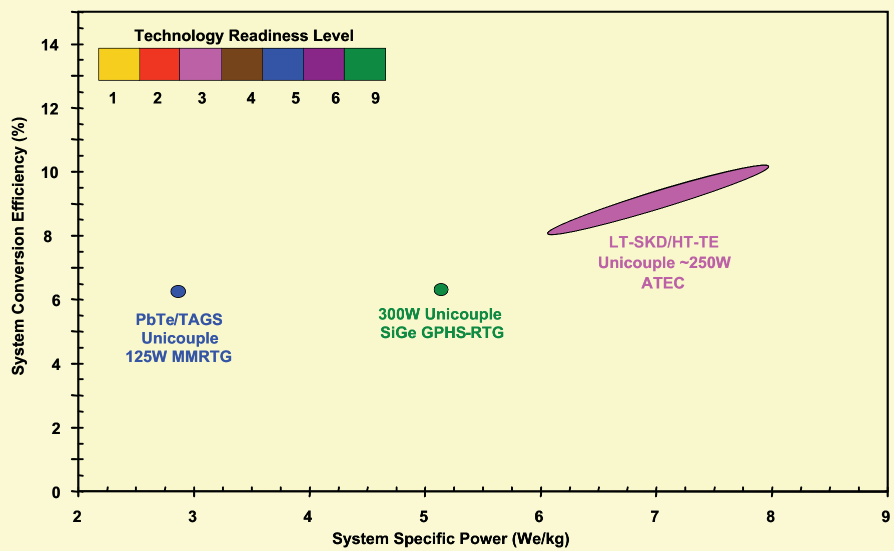
- **Near Term Advanced RTG Development Project**
  - **Advanced Thermoelectric Converter (ATEC) Development**



- **Far Term Advanced RTG Development Tasks**
  - **Si-Ge Nanocomposites**
  - **Advanced Thermoelectrics R&T**



Advanced Thermoelectric Converter (ATEC)



Major Objectives:

- Develop and demonstrate advanced thermoelectric converter capable of supporting a deep space RTG with 6-8 We/kg and 14 year lifetime.
- Develop and demonstrate couple with 11-12% conversion efficiency
- Demonstrate at least 1 year of lifetime operation on both couples and 4-couple modules
- Prediction of maximum of 22% power degradation (including isotope decay) over 14 years

Benefit: 110-180% RTG Specific Power Increase and 28 - 60% system conversion efficiency increase over MMRTG

PM: Rao Surampudi

PI: Thierry Caillat

Participating Organizations: JPL, GRC, USC, MSFC, Systems contractor

Milestones:

FY'06 Select primary & back-up high temperature TE materials

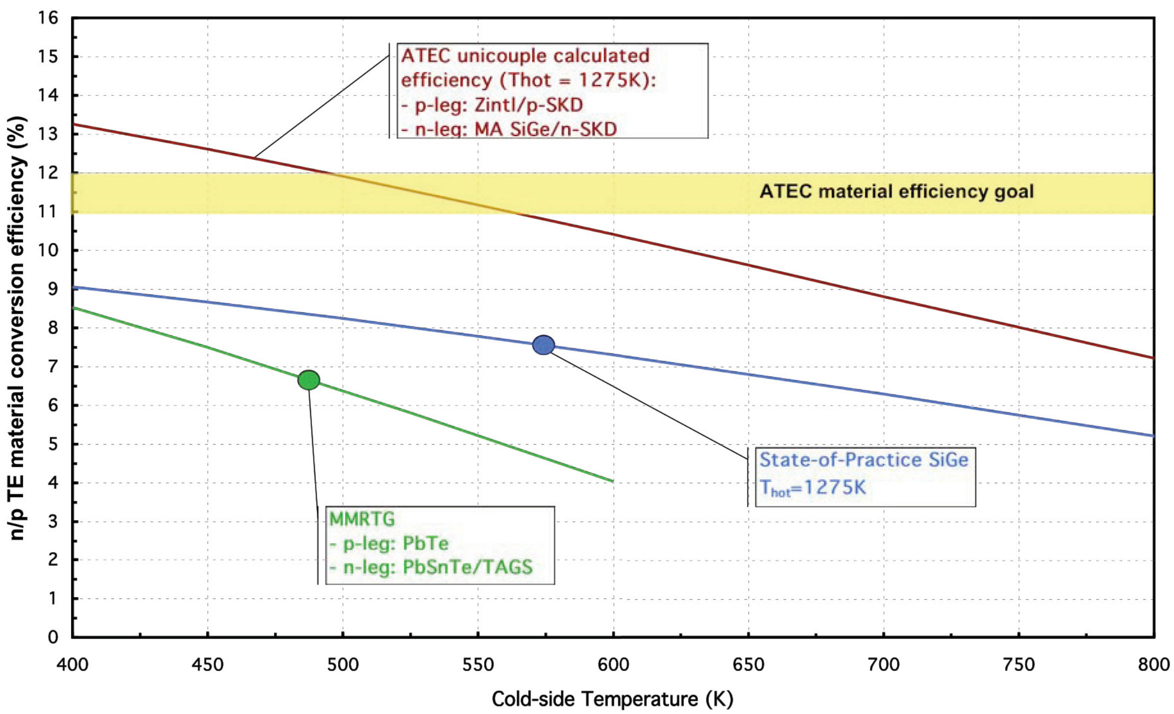
FY'07 Develop updated TE materials database
Validate couple power output within 10% of predict

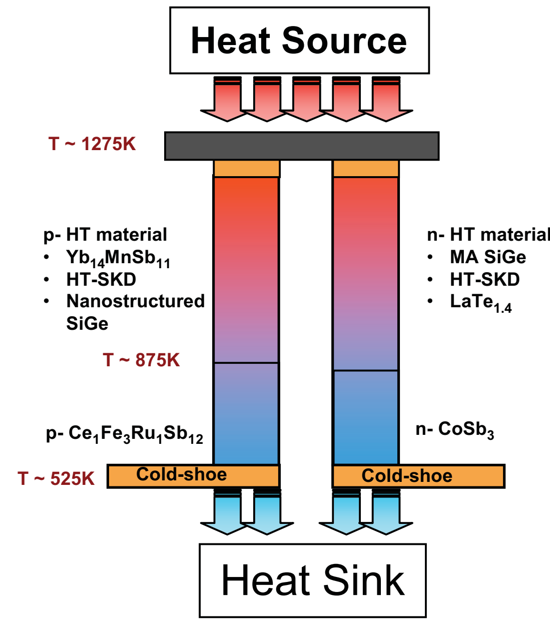
FY'08 Validate 4-couple module power output within 10% of predict
Complete couple fabrication and assembly specification

FY'09 Validate 1 year of couple life with < 0.33% degradation

Projected Performance

- High ZT(>1.0) thermoelectric materials
  - Higher efficiency
- Segmented couples
  - Each segment optimized for maximum performance
- Large Delta T: (1275 to 525 K Operation)
  - Higher efficiency
- Sublimation Control
  - Aerogel
  - Metal/metal oxide coatings





Synthesis Approach for Scalability

Spex High Energy Ball Mill

- **Vial load capacity 10 – 15g**
- **Double vials system**
- **Back-and-forth shaking motion**
- **Balls impact with powder and vial**
- **~ 1200rpm, vial swing ~ 5cm**
- **Making the force of the balls impact very high**

Spex Mill

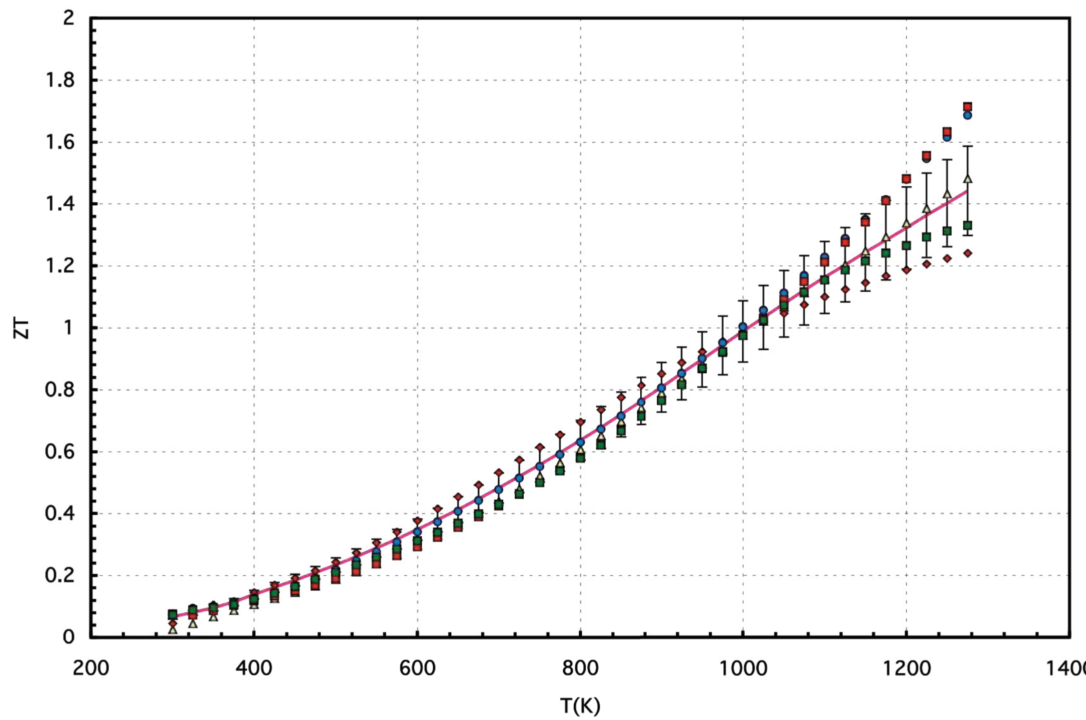
Planetary Low Energy Ball Mill

- **Vial load capacity – few hundred grams**
- **Two or four vials system**
- **Planet-like movement of its vials**
- **Centrifugal force produced by the vials rotating around their own axes and produced by the rotating support disk both act on the vial content**
- **Low impact synthesis process**

Planetary Mill

High Temperature Thermoelectric Materials Results: p- type Zintl

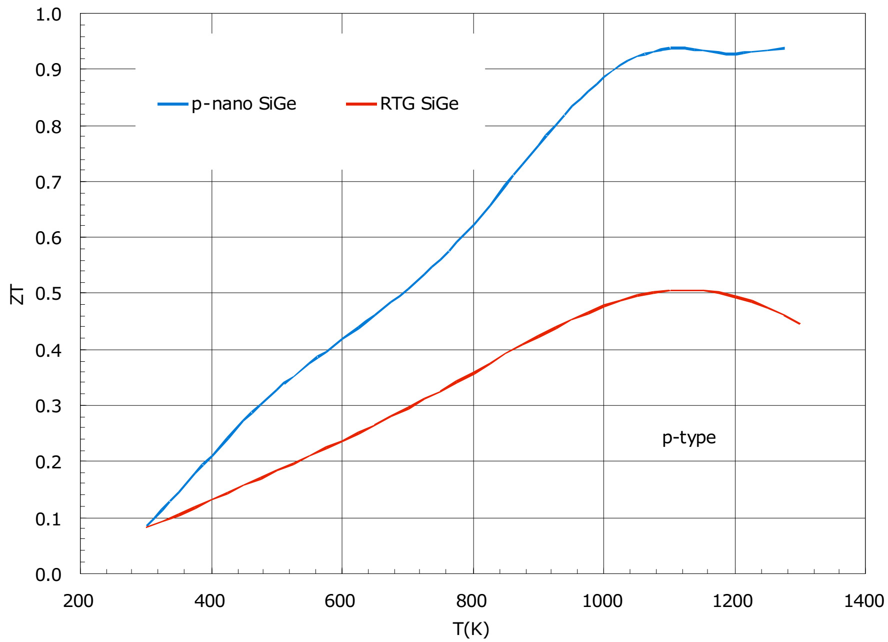
- Thermoelectric Properties
  - ZT > 1 at 1275K
- Synthesis process
  - Mechanical alloying
- Reproducibility
  - TE properties reproduced on >10 batches
- Scalability
  - 15g batches demonstrated
  - 50g batches by end of 2006
- Mechanical Properties
  - Initiated Young and shear modulus, Poisson's ratio, fracture toughness, flexural strength
- Sublimation
  - BOL (~ 5 x10^{-3} g/cm^2 /hr at 1275K)
- Segmentation
  - Co-hot-pressed several legs (promising)
- Some remaining challenges
  - Achieve sublimation goal of ~ 10^{-7} g/cm^{-2} /hr through use of sublimation suppression coatings
  - Demonstrate TE property stability over time
  - Segmentation to low-T SKD material



ZT values for $Yb_{14}MnSb_{11}$ material

High Temperature Thermoelectric Materials: p - type NanoSiGe (MIT/JPL)

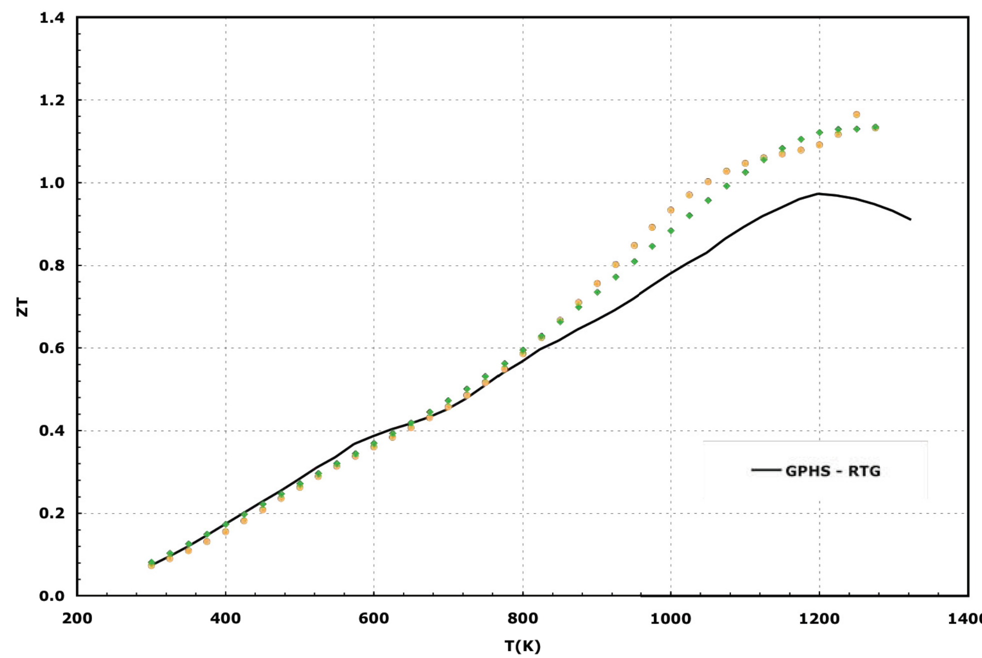
- Thermoelectric Properties
  - ZT approaching 1 at 1275K
- Synthesis process
  - Mechanical alloying
- Reproducibility
  - In progress
- High temperature Stability
  - Demonstrated stability of TE properties for 750 hrs at 1275K under MIT / JPL NRA task
- Scalability
  - 15g batches demonstrated
  - 50g batches by end of 2006
- Mechanical Properties
  - Will be initiated by end of 2006
- Sublimation
  - Plan to measure BOL sublimation and compare with RTG materials
  - Si_3N_4 coatings (GPHS-RTG SiGe)
- Segmentation
  - GPHS-RTG heritage – for metallization
  - Need to develop segmentation to low-T SKD if needed
- Remaining challenge:
  - Demonstrate batch to batch reproducibility and scalability
  - Further demonstrate TE property stability over time



Potential Backup material for Zintl

High Temperature Thermoelectric Materials: n - type SiGe

- Thermoelectric Properties
  - ZT ~ 1.1 at 1275K
- Synthesis process
  - Mechanical alloying
- Scalability
  - 15g batches demonstrated
  - 50g batches by end of 2006
- Reproducibility
  - ZT ± 10% of 4 consecutive batches
- Sublimation
  - Si_3N_4 coatings used for GPHS-RTG SiGe
  - Plan to measure BOL sublimation and compare with GPHS-RTG SiGe
- Segmentation
  - RTG heritage – for metallization
  - Need to develop segmentation to low-T skutterudite
- Mechanical Properties
  - Measurements initiated
  - Expected to be similar to GPHS-RTG SiGe
- Issues / concerns
  - Achieve higher ZT > 1 at 1275K



Improved mechanically alloyed SiGe

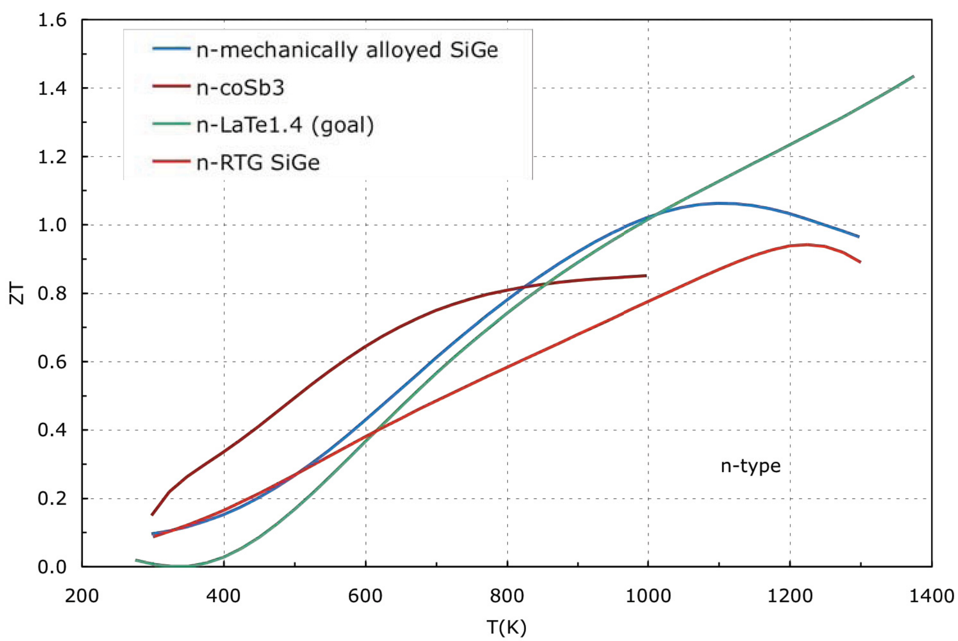
High Temperature Thermoelectric Materials
n - type $LaTe_{1.4}$

- Thermoelectric Properties
  - Not measured yet for optimized samples
  - Goal is ZT ~ 1.2 at 1275K
- Reproducibility
  - Not yet
- Scalability
  - 15g batches
- Mechanical Properties
  - Not yet
- Sublimation
  - Not yet
- Segmentation
  - Not yet
- Remaining challenges
  - Develop reproducible mechanical alloying synthesis process
  - Optimize TE properties by controlling La to Te ratio

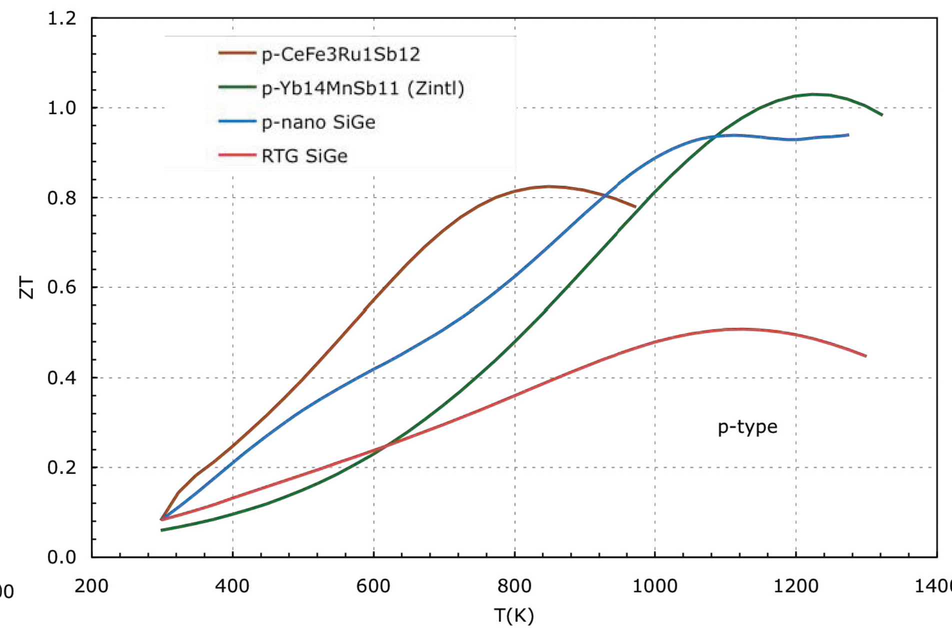
N-$LaTe_{1.4}$

- **Potential backup for mechanically alloyed n- SiGe**
- **Pay back is potentially high since this material offers high ZT > 1 at high temperatures**

ZT summary

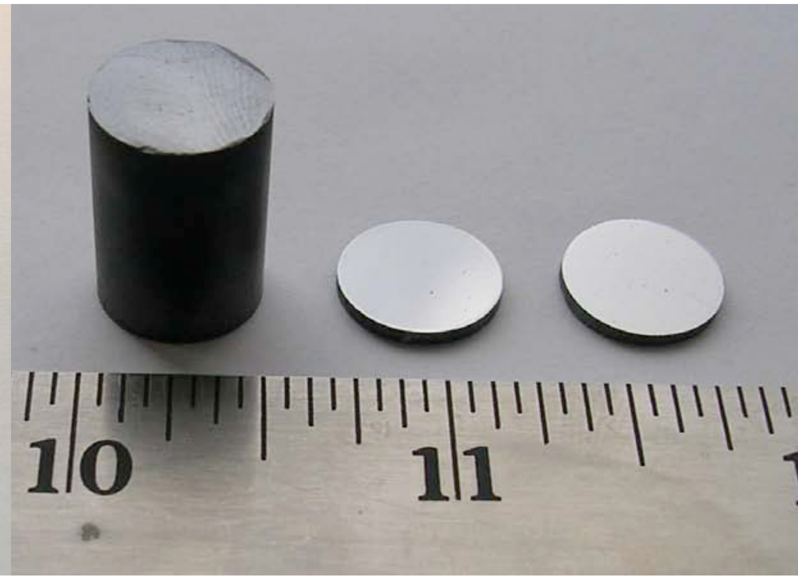


n-mechanically alloyed SiGe
n-coSb3
n-LaTe1.4 (goal)
n-RTG SiGe
n-type
ZT
T(K)



p-CeFe3Ru1Sb12
p-Yb14MnSb11 (Zintl)
p-nano SiGe
RTG SiGe
p-type
ZT
T(K)

Low-T skutterudite development

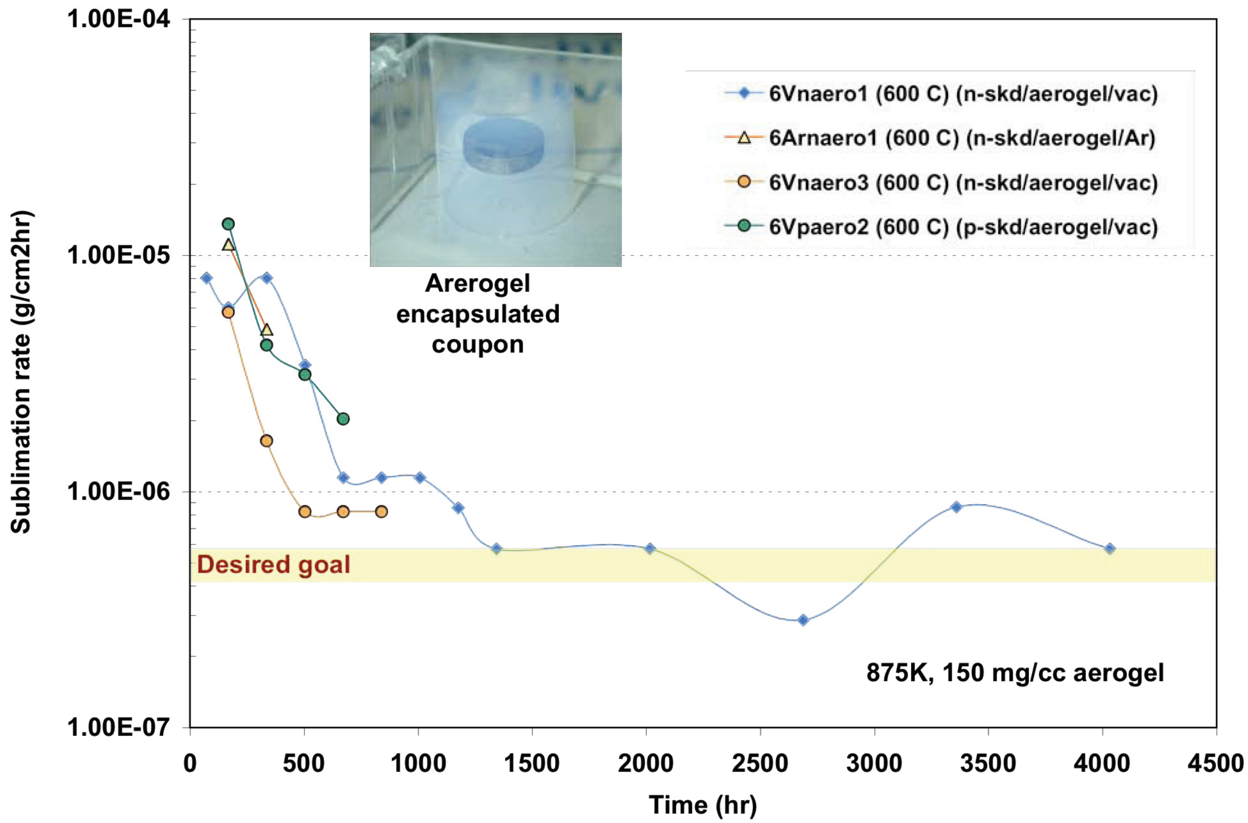


Mechanical Properties
40mm x 7mm puck

Sublimation Suppression Control Disks
12mm x 1.5mm disks

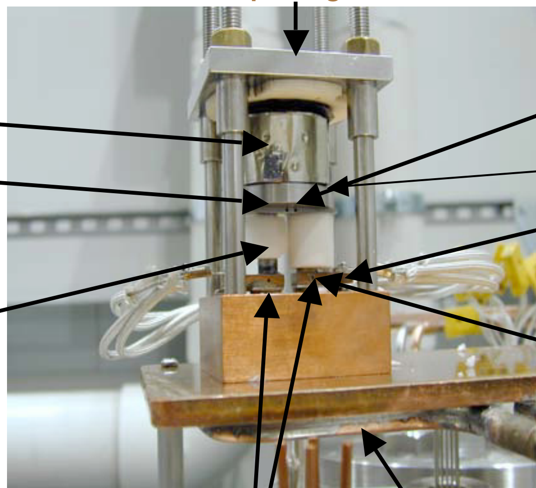
CTE and Compression
6.4mm x 25mm

Sublimation Rates Life Tests at 875 K for n- and p-type low-T SKD Aerogel Encapsulated Coupons



- Demonstrated that the desired sublimation rate (<5 x 10^{-7} g/cm^{2}hr) for 14 years of operation can be achieved up to 875K for aerogel-encapsulated low-T skutterudites after up to 4000 hours of testing

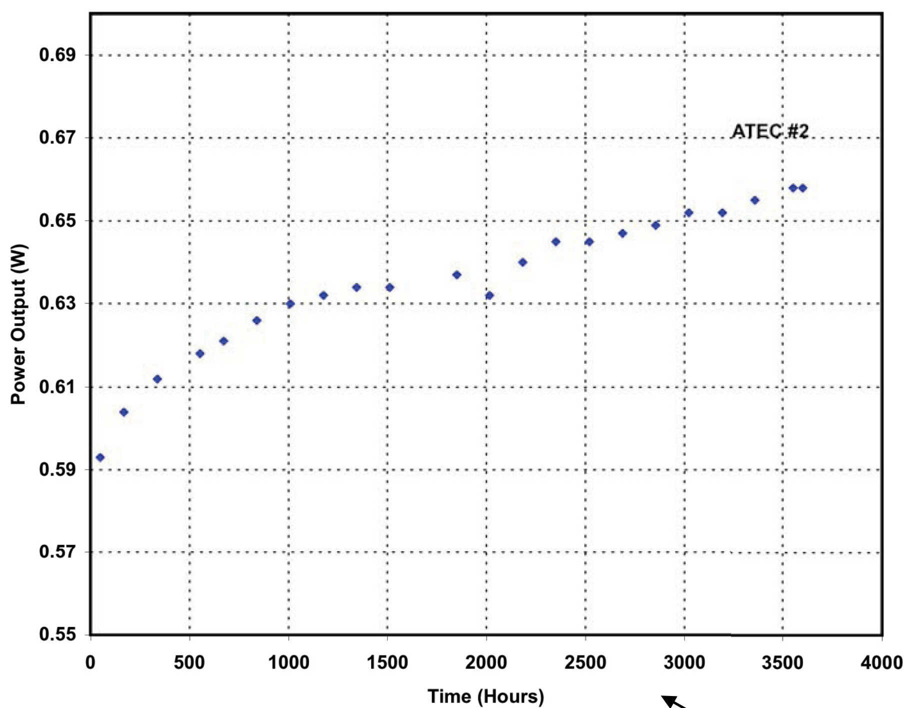
Low-T skutterudite -unicouple performance testing

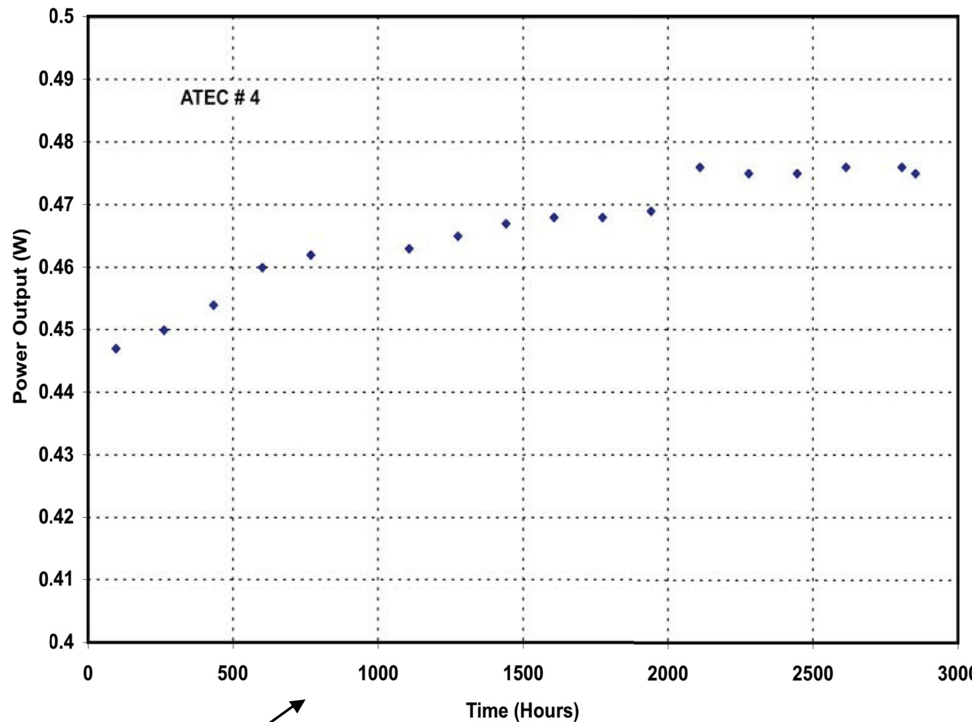


Skutterudite unicouple with Nb hot-shoe

- **Initiated performance life testing of spring-loaded low-T skutterudites unicouples**
  - **In-gradient testing with T_{Hot} ~ 875 K ± 10K and T_{Cold} = 300 K ± 10K**
  - **Vacuum environment (10^{-6} Torr)**
  - **Power output vs. load current at constant hot-shoe temperature**

Low-T skutterudite unicouple performance life testing





- **ATEC 2:**
  - P-leg: $CeFe_3Ru_1Sb_{12}$
  - N-leg: $CoSb_3$
  - T_{hot} ~ 925K
  - T_{cold} ~ 300K

Skutterudite unicouple with Nb hot-shoe

- **ATEC 4:**
  - P-leg: $CeFe_3Ru_1Sb_{12}$
  - N-leg: $CoSb_3$
  - T_{hot} ~ 875K
  - T_{cold} ~ 300K

Summary

- **Summary**
  - **RTG's have enabled surface and deep space missions since 1961**
    - **26 flight missions without any RTG failures**
    - **Mission durations in excess of 25 years**
  - **Future NASA missions require RTG's with high specific power and high efficiency, while retaining long life (> 14 years) and high reliability**
    - **6-8 W/kg, 10-15% efficiency**
  - **JPL in partnership with NASA-GRC, NASA-MSFC, DOE, Universities and Industry is developing advanced thermoelectric materials and converters to meet future NASA needs**

- **Acknowledgements**
  - **NASA Science Missions Directorate/ Radioisotope Nuclear Systems and Technologies**